

Stability of gas discharge channels for final beam transport

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Abstract

Discharge plasma channels have been investigated in recent years at Gesellschaft für Schwerionenforschung–Darmstadt (GSI) and at the Lawrence Berkeley National Laboratory in Berkeley, California, in a number of experiments. A short summary of the experimental work at Berkeley and GSI is given. Different initiation mechanisms for gas discharges of up to 60 kA were studied and compared. In the Berkeley experiments, laser ionization of organic vapors in a buffer gas was used to initiate and direct the discharge while at GSI, laser gas heating and ion-beam-induced gas ionization were tested as initiation mechanisms. These three initiation techniques are compared and the stability of the resulting discharge channels is discussed. A discharge current of 50 kA, a channel diameter well below 1 cm, a pointing stability better than 200 μm , and MHD stability of more than 10 μs have been demonstrated simultaneously in the recent experiments. These parameters are sufficient or close to the requirements of a reactor application depending on the details of the target design. The experimental results show that transport channels work with sufficient stability, reproducibility, and ion optical properties for a wide pressure range of discharge gases and pressures.

Keywords: Discharge channels; Final beam transport; Laser initiated discharge channels; Neutralized beam transport

1. INTRODUCTION

Various methods for chamber transport and final focusing of heavy ion beams have been proposed and are currently under investigation. Pure ballistic transport in hard vacuum ($p < 10^{-5}$ mbar) as proposed in the Heavy Ion Beams and Lithium Lead (HIBALL) studies seems today impractical in a reactor with a repetition rate of several hertz. The differences in low-gas-density chambers with nearly ballistic transport are currently under investigation, but stripping is critical for this transport mode. The HILIFE-II reactor design is based on low chamber gas density and ballistic or nearly ballistic transport (Moir, 1991). The problems of conventional quadrupole final focusing have also been identified in the European Heavy Ion Driven Inertial Fusion (HIDIF) study on heavy ion drivers for inertial confinement fusion. Neutralized beam transport in discharge channels is considered to be an alternative approach to ballistic focusing in this study by Tauschwitz *et al.* (1998).

One important feature of final focusing based on discharge channel transport is the possibility of merging sev-

eral individual beams in a neutralizing environment, reducing the number of beams that penetrate the reactor chamber. This possibility is mainly related to the large acceptance of the system, which allows the transmission of beams with an initial angle to the transport channel axis.

A further advantage of the plasma-based focusing system is the large acceptance in longitudinal phase space. Since the target hydrodynamics requires short ion bunches on the order of 10 ns, the beam from the accelerator has to be bunched by a large factor. This leads to a large momentum spread of the beam and produces, for example, chromatic aberrations in the final focusing system. The design of achromatic lens systems for these beams is difficult and expensive (Ho & Crandall, 1993). The neutrons that enter the beam lines in a channel-based reactor can be reduced by an order of magnitude, and thus the shielding of the focusing magnets and activation problems are strongly decreased. These advantages ease the requirements on accelerator and reactor systems. This can lead to simpler technical solutions for the construction of the driver, which mainly determines the cost of an IFE power plant.

Motivated by these advantages, neutralized beam transport and focusing in gas discharge plasmas have been under investigation for heavy ion beam fusion since 1995 at the Lawrence Berkeley National Laboratory (LBNL)

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by Tauschwitz *et al.* (1995) and at Gesellschaft für Schwerionenforschung–Darmstadt (Tauschwitz *et al.*, 1999) following extensive work on discharge channel transport for light ion beams that was done at Sandia, the Naval Research Laboratory, and Osaka mainly in the years from 1977 to 1983. Figure 1 shows schematically the key elements of such a focus and transport system for an IFE reactor. Beam combining is done at the entrance of an adiabatic plasma lens outside of the reactor which reduces the beam diameter to the desired focal spot size on the target. The adiabatic lens is then extended into an laser-initiated discharge channel which transports the beam at constant diameter through the chamber to the target. First experimental work on channel formation and stability at LBNL by Tauschwitz *et al.* (1996) and by Vella *et al.* (1998) was paralleled by engineering design of a modified HILIFE-II reactor with discharge-channel-based final beam transport (Peterson *et al.*, 1998). A point design of a reactor system was developed by Yu *et al.* (1998) including the beam optics of the transition from the conventional beam transport to the plasma transport system (Henestroza *et al.*, 1998). The proposed system is consistent with a target design studied by Tabak and Callahan-Miller (1998). Ignition with a yield of over 400 MJ is predicted for a 6.5-MJ drive with a 4.4-MJ main pulse with 4 GeV Pb ions delivered in 8 ns onto a two-sided target with 5-mm radius spots. The main pulse is preceded by a 3-GeV,

30-ns prepulse with 2.1 MJ. For the reactor scheme, a modified HYLIFE-II reactor was considered, filled with 5 Torr Xe gas with two small (3-cm radius) holes on opposite sides of the reactor for beam entry. A set of oscillating and steady Flibe jets provide 4π coverage of the reactor walls, except for the small holes for beam entry and current return paths.

2. CURRENT WORK AT GSI DARMSTADT AND LBNL

Recently PhD theses have been finished at LBNL by Ponce (2002) and at GSI by Niemann (2002a) and Penache (2002). The LBNL work concentrates on the investigation of the dynamical properties both of the neutrals and the ions of a laser-induced discharge in a mixture of nitrogen and benzene. The density depression before ignition of the main discharge is created by an electrical prepulse which is mandatory in this experiment. The prepulse reduces the gas density in the channel by an order of magnitude. The stability of the high current discharge is attributed to the high gas density that surrounds the central depression channel. The current distribution in the channel was investigated by measuring the Faraday rotation of a CO₂ laser beam intersecting the discharge channel.

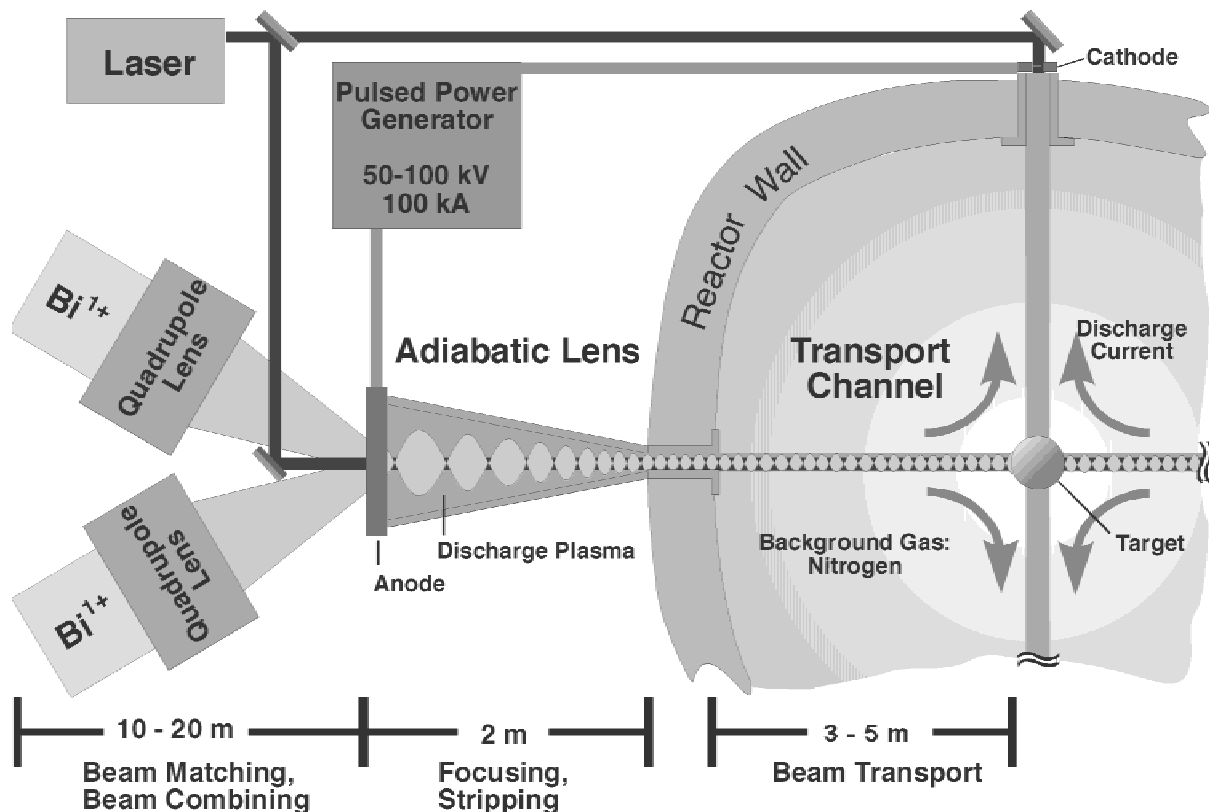


Fig. 1. Principle layout of a heavy ion driven IFE reactor with plasma lens focusing and discharge channel final transport.

The work by Niemann describes both the Berkeley and the Darmstadt experiments and concentrates on the plasma diagnostics by interferometry, schlieren diagnostics, Faraday rotation, and a spectroscopic time-resolved temperature determination by spectroscopy using a rate equation model. Different channel initiation methods using gas ionization and gas heating by a laser as well as gas ionization by an ion beam are described. First experiments on intersecting discharge channels are described which show that the discharge configuration must be symmetrical so that magnetic forces on the channels cancel and that the breakdown risk between channels is small. In a proof-of-principle experiment, an ion beam was transported through one of the intersecting channels without problems.

The work by Penache was done at the channel transport experiment at GSI and emphasizes the ion beam transport properties using the UNILAC accelerator. In several runs, different ion species with an energy of 11.4 MeV/u were transported through the 50-cm discharge channel. At the time of peak current (up to 60 kA), the ions undergo more than one full betatron oscillation in the short channel. The transport properties investigated are spatially resolved by using a pepperpot mask in front of the channel. The resulting beam pattern of the single beamlets on a scintillator behind the channel are interpreted by a Monte Carlo simulation of the beam transport. The results are compared to magnetic probe measurements in the discharge channel.

Some results on the plasma diagnostics for the GSI experiment are summarized by Niemann *et al.* (2002b), and the most important fact of the beam transport experiments are described by Penache *et al.* (2002). In the following sections, different channel initiation mechanisms are compared and the stability of the discharge channels is described, which is a key issue to make discharge channel transport a viable concept for ion beams.

With measurements of temperature, electron density, gas density, and magnetic field distribution in the channels and the comparison with results of beam transport experiments at GSI, the channel transport principle is well characterized by experimental data over a wide range of discharge conditions.

3. DISCHARGE CHANNEL INITIATION BY LASER IONIZATION OF THE DISCHARGE GAS

The obvious way to induce and to direct a gas breakdown is to ionize the gas along the desired breakdown path. There are different ways to ionize a gas with a laser. Unfortunately none of them is very efficient, either because the required lasers are not very efficient or because the ionization process has a low cross section. One of these possibilities is direct ionization by single photon absorption. With few exceptions, like the ionization of alkali vapors, a laser in the VUV range is needed for this scheme. An alternative is the ionization by two photon absorption, which is possible for

many organic molecules using excimer lasers. This approach was extensively tested and investigated at Berkeley.

Some molecular gases like ammonia can be efficiently heated in the IR region, where the gas molecules have strong absorbing rotation or vibration levels. Due to the temperature increase, a small amount of thermal ionization can be expected. Finally, short pulse lasers can be used to achieve field ionization along the laser path in the gas. This last possibility has the advantage that the choice of the discharge gas is not limited by the initiation technique.

4. DISCHARGE CHANNEL INITIATION BY THERMAL GAS EXPANSION

Although experimentally very similar to the above-mentioned gas ionization by a laser, the physics of discharge initiation by thermal gas expansion is very different. For this approach, the discharge gas is heated by a laser along its path. Only a few laser-gas combinations allow an efficient heating of the gas. The combination chosen for the experiments at GSI was a line-tunable CO₂ laser and ammonia gas, following similar work at Sandia by Olsen and Baker (1981). The laser was tuned to the maximum absorption and had an pulse energy of 5 J. Details of the discharge initiation for the GSI experiment are described by Niemann *et al.* (2002b). An experimental advantage of discharges in ammonia is that all discharge products are gaseous and can easily be removed by a vacuum pump leaving a clean discharge chamber. Discharge gases containing hydrocarbons produce a soot layer on all surfaces which alters the voltage breakdown of insulators, absorbs the laser light at the entrance window, and deteriorates the access for optical diagnostics within a few discharges. Therefore systematic investigations of the discharge initiation are very difficult for gases containing hydrocarbons.

At GSI, the breakdown initiation was investigated for different discharge delays with respect to the laser pulse and for different laser intensities. It was found that a well-defined minimum delay between laser and discharge trigger exists. A discharge that is triggered before this minimum delay time does not ignite or ignites with a very large jitter. This minimum delay is in the range of 10 to 20 μ s, depending on the gas pressure. With the help of hydro simulations using the CYCLOPS code, the delay is identified as the expansion time of the laser-heated gas to the minimum on-axis density. The process of gas expansion was directly observed by interferometry by Niemann *et al.* (2002b). The interferometry shows that the expanding gas forms a steep gas wall surrounding a density depression zone along the laser path. The development of the gas depression channel was investigated by S. Neff, A. Tauschwitz, C. Niemann, D. Penache, D.H.H. Hoffmann, S.S. Yu, and W.M. Sharp (submitted) measuring the small angle scattering of the UNILAC heavy ion beam in this channel. Both the interferometric and the beam scattering measurements show a density variation in agreement with simulation using the CYCLOPS code assuming a 500 to 800 K gas heating by the laser.

5. DISCHARGE CHANNEL INITIATION BY IONIZATION OF THE DISCHARGE GAS WITH AN ION BEAM

Stable discharge channels were initiated by an ion beam pulse from the UNILAC-linear accelerator at GSI, which creates a trace of seed electrons along the desired path of breakdown. For these experiments, an ion beam with a 2-mm diameter aligned exactly to the channel axis was used to prepare the ionization channel. In this way, discharges were created in ammonia and argon gas. The discharge was triggered 20 μs after the beginning of a 50- μs -long ion beam pulse with an electric current of less than 5 μA inside the 50-cm-long discharge chamber. An upper limit for the electron density induced by the beam can be estimated from the total energy loss of the beam ions in the gas. At an ammonia gas pressure of 10 mbar, the total energy loss of the beam within 20 μs is about 10^{14} eV/cm³. Neglecting recombination of free electrons and assuming that the whole energy is used to ionize only electrons with the lowest ionization potential, the maximum electron density becomes roughly 10^{13} cm⁻³. Even if the real density is one order of magnitude lower, the value is comparable or even higher than the electron densities produced by UV-laser-induced ionization of

organic molecules that was used for the channel initiation in the LBNL experiments.

The discharges were found to be stable and reproducible even at very late times in both ammonia and argon at currents exceeding 50 kA. Channels in NH₃ could only be produced at pressures up to 5 mbar. The pressure in Ar discharges was only limited by the differential pumping system. Figure 2 shows fast-shutter pictures of discharges in NH₃ and Ar at different times after breakdown. Even after the current reversal of the ringing discharge current, the channels show no sign of instabilities. The discharge current as well as the channel diameter evolution for discharges in ammonia and argon with and without using an additional electrical prepulse are compared in Figure 3. The prepulse creates a density depression channel along the ion beam ionized path like in the Berkeley experiment, but it shows no influence on the discharge stability. For both gases, the prepulse only leads to an increased channel diameter of the final high current discharge due to the lower initial gas pressure which leads to a faster channel expansion. Without a prepulse, the initial diameter of the high current discharge is in all cases comparable to the size of the 2-mm ion beamlet. The diameter of discharges in argon is considerably smaller than in ammonia, which is important for beam trans-

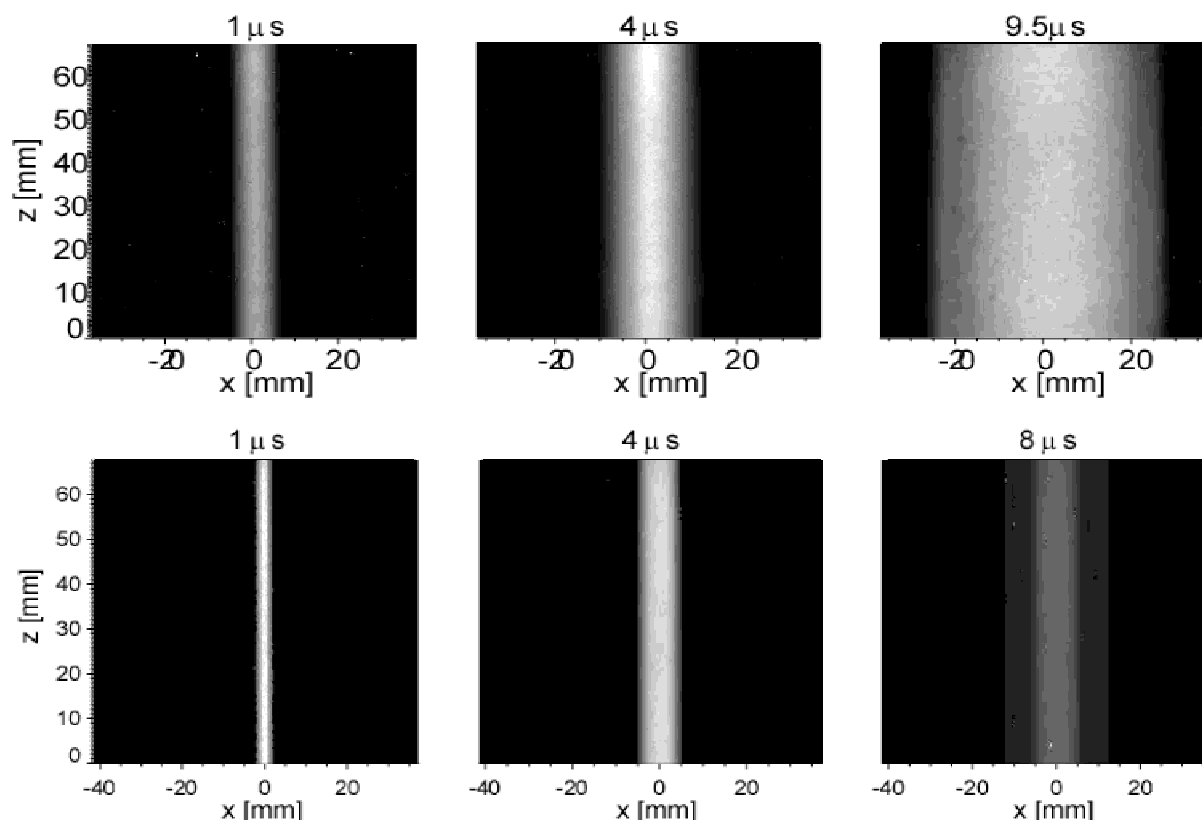


Fig. 2. Fast-shutter images of beam-initiated discharge channels in ammonia (top row) and in argon (bottom row). The current maximum of 50 kA is reached at 4 μs .

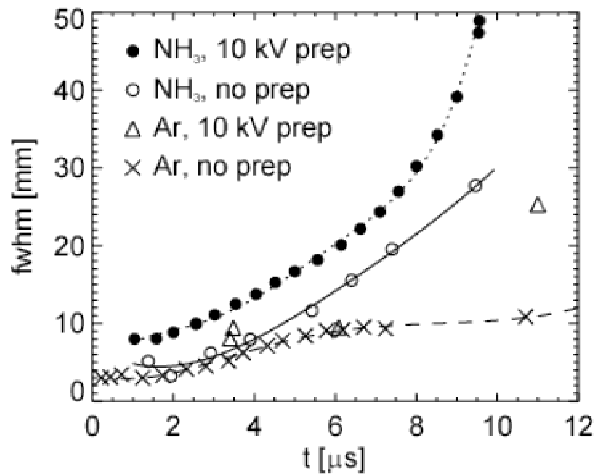


Fig. 3. Channel diameter (FWHM) as a function of time for discharges in ammonia and argon with and without an electrical prepulse.

port in heavy ion fusion since the channel diameter limits the beam spot size on the target.

Besides typical MHD instabilities, the discharge channels show a shift of the channel axis during the discharge. For laser-initiated channels, this shift of the axis can be several millimeters. This observation was made by fast-shutter

images of the plasma light emission recorded side-on and confirmed by a deflection of the transported ion beam. Beam initiated channels in NH₃ show only a shift of about $\pm 200 \mu\text{m}$, for Ar discharges this shift is reduced to about $\pm 100 \mu\text{m}$. Discharges in other gases like N₂, He, Kr, and Xe have been successfully initiated but need further investigation to determine their stability. The transverse stability of the discharge axis is of importance for a fusion reactor, where the beam must hit a millimeter-sized target.

The improved stability, the simple initiation mechanism, and the possibility of creating channels in any gas make ion beam initiation of the discharge especially interesting for heavy ion fusion. The beam currents that are required for the discharge initiation are easily produced and do not preheat the fusion target.

6. DISCHARGE CHANNEL STABILITY

The MHD stability of discharge channels is crucial for ion beam transport. The dominant type of instability in all investigated channels was the kink ($m = 1$) instability. To investigate the growth rate of this instability, the channels were recorded side-on with a framing camera. Results for different ammonia pressure are shown in Figure 4. Below a pressure of 15 mbar, no instabilities were observed during

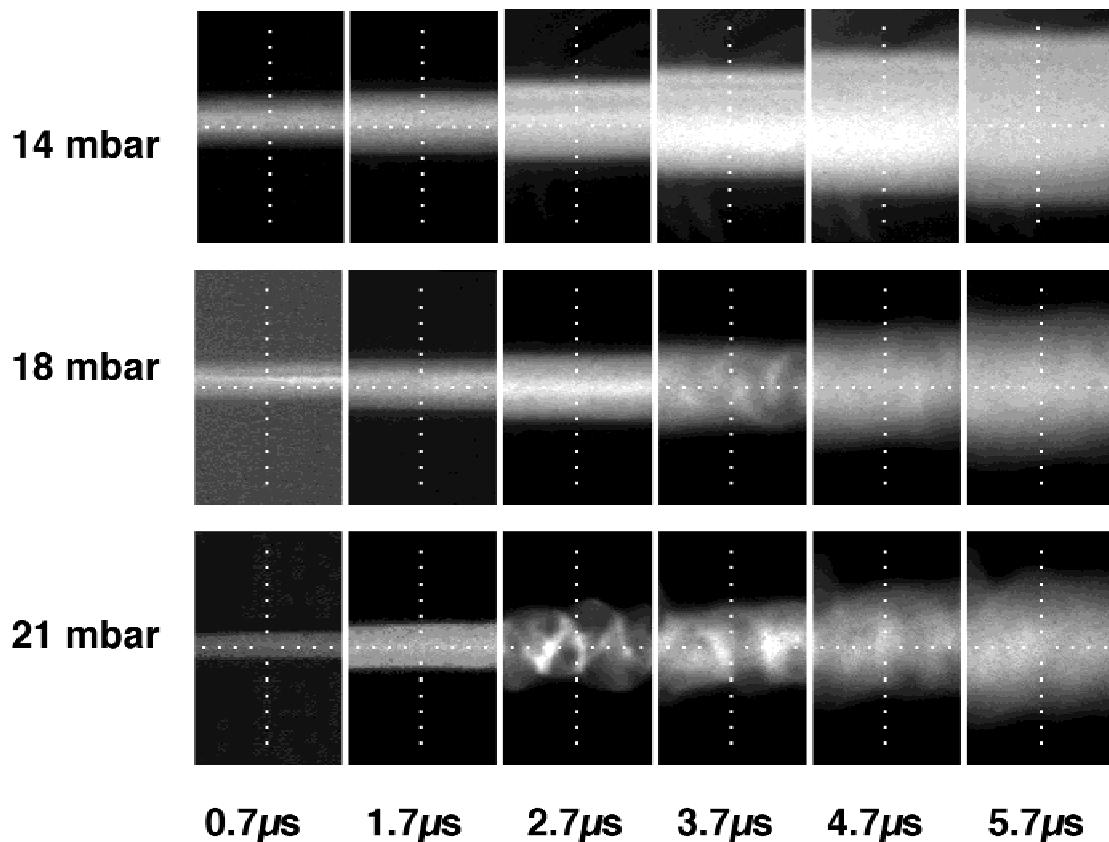


Fig. 4. Framing-camera pictures of discharges in 14-, 18-, and 21-mbar ammonia gas.

the first half wave of the current pulse. For a pressure of 18 mbar, instabilities were found in about 25% of the channels. These instabilities usually start to become visible around the time of peak current at about 4 μ s. At a pressure of 21 mbar, the instabilities appear between 2 and 3 μ s after ignition and are observed in all discharges.

This increasing growth rate of instabilities with increasing gas pressure is unexpected, but a scaling law derived by Manheimer *et al.* (1973) shows that the growth rate depends on many variables which are all interconnected in a rather complex way:

$$\Gamma \propto k \frac{B_\Phi}{\sqrt{\mu_0 n_i m_i}} \left(\frac{\rho_{ch}}{\rho_g} \right)^{1/2}.$$

Here Γ is the growth rate of an instability with wave number k for an azimuthal magnetic field of B_Φ , an ion density n_i , and a mass of the ions m_i . If the discharge takes place in a channel with initial gas density ρ_{ch} which is surrounded by a gas of density ρ_g , the growth rate is reduced by the higher mass of the surrounding gas. With this scaling, the growth rate depends on the ionization degree, the radial current distribution, and, in case of a molecular discharge gas like ammonia, on the gas chemistry and on the gas density profile before and during the discharge. These quantities de-

pend on the local temperature and conductivity distribution in the plasma.

In addition to the framing pictures, the channel stability was investigated using the ion beam deflection. This was done by imaging the location of an ion beamlet on a scintillator behind the discharge chamber. The azimuthal magnetic field of the discharge causes betatron oscillations of the beamlet which are centered around the discharge axis. If the discharge is aligned with the beam axis, the image of the beamlet on the scintillator changes in size but remains at a fixed position for all times during the discharge current oscillation. For an unstable channel which moves around its initial axis, the beamlet also moves on the scintillator. Figure 5 compares time-integrated scintillator images for laser- and ion-beam-initiated discharges in NH_3 and for ion-beam-initiated channels in Ar with and without electrical prepulse. The exposure time of the pictures started 1 μ s before breakdown and extended over the first half wave period of the discharge.

Laser-initiated discharges typically exhibit shifts of the beam position on the scintillator of up to 2 mm when an electrical prepulse is used. This situation is slightly improved without the prepulse. Although the use of a prepulse reduces the growth of MHD instabilities by the factor $(\rho_{ch}/\rho_g)^{1/2}$, it facilitates the shift of the channel axis due to

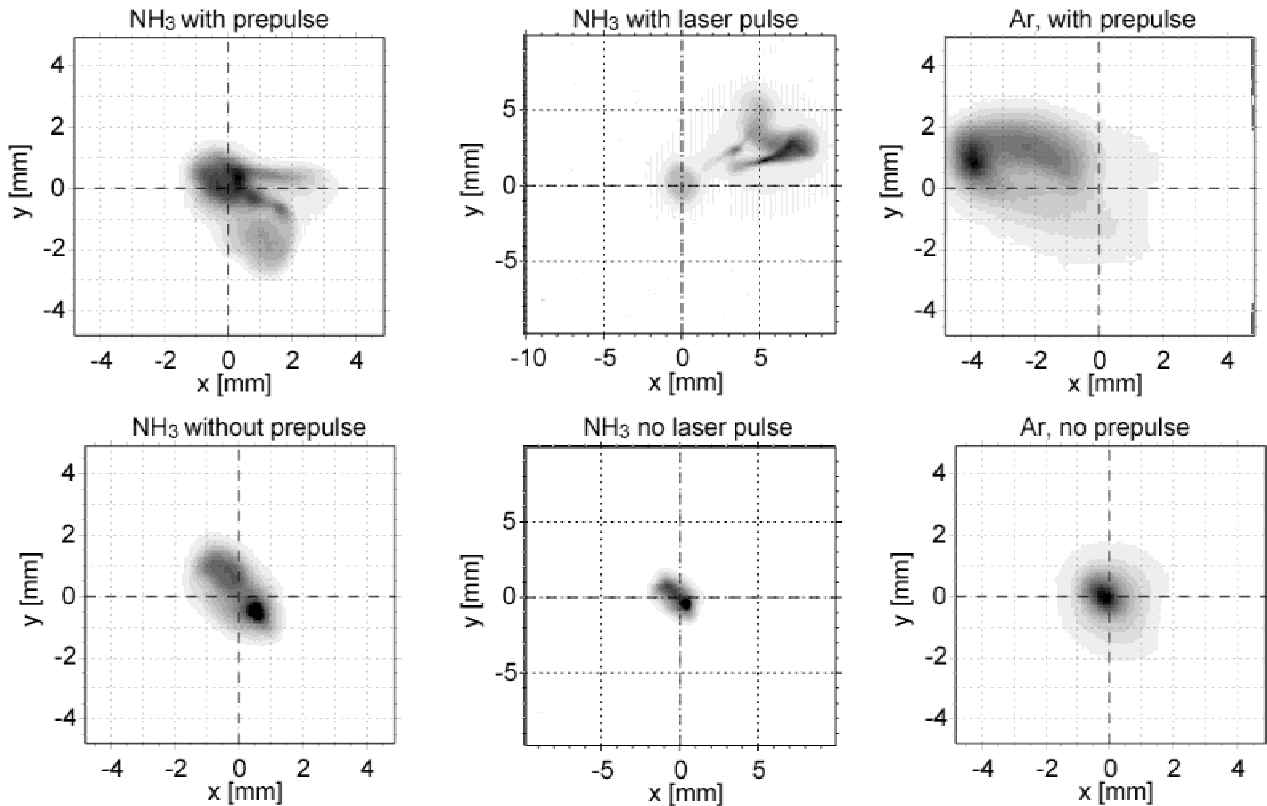


Fig. 5. Scintillator images of an ion beam propagating through different channels. The motion of the beamlet on the scintillator was integrated over the first current half wave. Left: laser-initiated ammonia discharges with and without prepulse; center: laser- and ion-beam-initiated ammonia discharges; right: ion-beam-initiated argon discharges with and without prepulse.

the reduced gas density in the gas depression channel. The same behavior is found in ion-beam-initiated channels in argon. Directly comparing laser- and ion-beam-initiated channels in ammonia shows the significantly better stability of the beam-initiated discharges. An explanation for this could again be the gas density depression by the laser which facilitates the movement of the channel axis within this density depression zone. Typically the shift of the discharge axis for beam-initiated channels is an order of magnitude smaller than the shift of laser-initiated discharges, in agreement with results of the framing camera investigations.

7. CONCLUSIONS AND PERSPECTIVES

The recent results at LBNL and at GSI on discharge characteristics and beam transport properties of laser- and ion-beam-initiated discharges show that discharge channel transport is a viable concept for the final beam transport in heavy ion fusion.

A number of topics needs close attention in the near future. All experiments so far were restricted to a channel length below half a meter while the required channels in a fusion reactor have to be a factor of ten longer. Experiments to extend the channels at GSI up to 2 m are planned in the same setup that is currently used. A second point is an intense study of channel instabilities. Since instabilities have been shown to depend on many details of the initiation scheme and discharge conditions, it would be desirable to investigate instabilities in an environment that is very similar to the anticipated reactor conditions. To achieve this goal discharge initiation by a short pulse laser has to be tested. Although field ionization by a short pulse laser is the envisaged method of choice for a fusion reactor, it has so far not been tested. First experiments are planned at GSI using the 10-J/500-fs pulse of the PHELIX preamplifier. These tests will allow us to investigate discharges in xenon gas and it will be possible to include the effects of a small partial pressure of other gases, like constituents of a molten salt mixture that will be present in a liquid wall reactor, on the discharge characteristics.

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